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Constraints on neutrino masses from the study of the nearby large-scale structure and galaxy cluster counts

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The high precision measurements of the cosmic microwave background by the *Planck* survey yielded tight constraints on cosmological parameters and the statistics of the density fluctuations at the time of recombination. This provides the means for a critical study of structure formation in the Universe by comparing the microwave background results with present epoch measurements of the cosmic large-scale structure. It can reveal subtle effects such as how different forms of Dark Matter may modify structure growth. Currently most interesting is the damping effect of structure growth by massive neutrinos. Different observations of low redshift matter density fluctuations provided evidence for a signature of massive neutrinos. Here we discuss the study of the cosmic large-scale structure with a complete sample of nearby, X-ray luminous clusters from our REFLEX cluster survey. From the observed X-ray luminosity function and its reproduction for different cosmological models, we obtain tight constraints on the cosmological parameters describing the matter density, Ω_m , and the density fluctuation amplitude, σ_8 . A comparison of these constraints with the *Planck* results shows a discrepancy in the framework of a pure Λ CDM model, but the results can be reconciled, if we allow for a neutrino mass in the range of 0.17 to 0.7 eV. Also some others, but not all of the observations of the nearby large-scale structure provide evidence or trends for signatures of massive neutrinos. With further improvement in the systematics and future survey projects, these indications will develop into a definitive measurement of neutrino masses.

Keywords: Cosmology, clusters of galaxies, neutrinos

1. Introduction

The recent high precision measurement of the cosmic microwave background (CMB) by the *Planck* satellite has provided tight constraints on the parameters of the cosmological model describing our Universe. A Λ CDM model with six parameters gives a very good description of the observations (Planck Collaboration 2015a). Therefore the structure of our Universe at the time of recombination (redshift of ~ 1090) is well defined. This opens the exciting possibility to study cosmic structure formation from the recombination epoch to the present and to look for very subtle effects, such as how different types of “Dark Matter” modify the growth of structure.

The currently most interesting of these quests is the study of the effect of massive neutrinos (e.g. Lesgourges & Pastor 2014, Abazajian et al. 2015).

Several studies of the nearby large-scale structure (LSS) of the Universe have found indications of a discrepancy between their results and the cosmological parameters obtained with Planck, most importantly for the cosmic matter density parameter, Ω_m , and the amplitude parameter of the matter density fluctuations on large scales, σ_8 . These results imply a smaller amplitude of the density fluctuations and often a slightly smaller matter density than what is obtained, if the structure characterised by Planck is evolved forward to the present epoch based on structure formation models for Λ CDM cosmology. These LSS studies involve assessments of the cosmic lensing shear (e.g. Haman & Hasenkamp 2013, Battye & Moss 2014), redshift space distortions seen in galaxy redshift surveys (e.g. Beutler et al. 2014, Ruiz & Huterer 2015), and the lensing of the CMB (Planck Collaboration 2015b). Most pronounced is the discrepancy for galaxy clusters (e.g. Burenin 2012, Planck Collaboration 2014, 2015c, Böhringer et al. 2014, Böhringer & Chon 2015).

The discrepancy of the Planck results and measurements of the present epoch LSS can in principle be reconciled by introducing massive neutrinos as a small fraction of Dark Matter. We know from neutrino oscillations observed for solar neutrinos, atmospheric neutrinos and in terrestrial experiments that neutrinos have mass, with a current lower limit for the sum of all three known neutrino families of $M_\nu = \sum m_{\nu_i} = 0.058$ eV (e.g. Lesgourges & Pastor 2014). The measurement of a useful upper limit from terrestrial experiments is currently out of reach, and we only have an upper limit for the mass of the electron neutrino of about 2 eV (e.g. Kraus et al. 2005). The study of the cosmic LSS already provides more stringent upper limits than this for the sum of all neutrinos, since neutrinos with such high masses would wash out too much of the LSS of the Universe (e.g. Riemer-Sørensen et al. 2013). A careful comparison of the LSS imprinted on the CMB at an early epoch with the LSS measured in the nearby Universe therefore opens thus the very exciting opportunity to obtain constraints on neutrino masses from astronomical observations.

In this paper we describe one of the most significant of these results obtained with our galaxy cluster redshift survey REFLEX (Böhringer et al. 2013, 2014), discuss the systematics of the results for galaxy clusters, and compare to other cosmological studies.

2. The effect of massive neutrinos on cosmic structure evolution

Massive neutrinos, as part of the Dark Matter in the Universe, have a clear effect on cosmological structure formation. The later the dark matter becomes non-relativistic, the more the smaller scales of Dark Matter fluctuations will be damped or washed out. The fact that relativistic Dark Matter particles can freely stream at the speed of light causes density fluctuations in this relativistic matter component to be erased on horizon scale. Therefore the main component of the Dark Matter

has to be “cold”, that is, has to become non-relativistic very early when the co-moving horizon size is smaller than galaxy scales, otherwise the galaxy population would look very different from what we observe. But a smaller admixture of hot Dark Matter, to which neutrinos are counted, would have until recently remained undetected by observations.

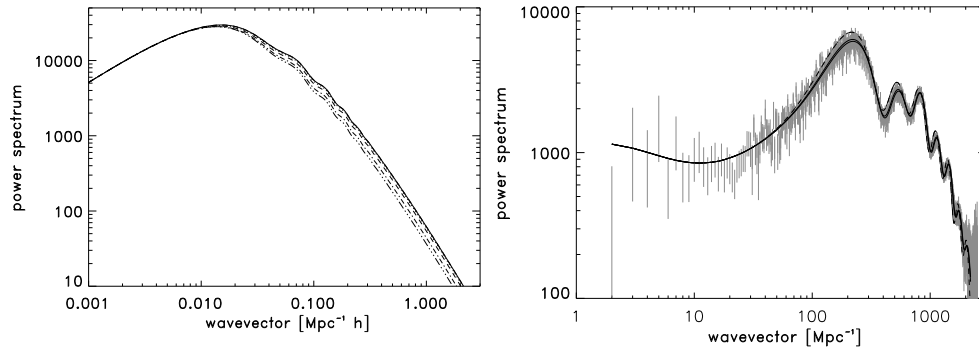


Fig. 1. **Left:** Effect of massive neutrinos on the present epoch matter density power spectrum. The solid curve shows the power spectrum for the sum of the neutrino masses, $M_\nu = 0.06$ eV, and the dashed lines show the cases for $M_\nu = 0.17, 0.4, 0.6$ eV, from top to bottom. **Right:** CMB power spectrum observed with Planck and model predictions for the best fitting cosmological parameters from the Planck survey for $M_\nu = 0$ and 0.6 eV (lower and upper solid line, respectively). The dashed line artificially amplifies the difference between the two solid lines by a factor of 5.

Neutrinos with a mass around 0.3 eV become non-relativistic at redshifts around 600 (e.g. Abazajian et al. 2015). Thus density structure in the neutrino matter component will be washed out on horizon scales well after recombination, which will affect the scales important for galaxy cluster formation. This effect on the matter power spectrum is shown in Fig. 1. The more massive the neutrinos are, the larger the dark matter fraction that is washed out, since the number density of cosmic neutrinos is fixed by the thermodynamics in the early Universe.

The effect of the neutrinos on the CMB power spectrum is much smaller, as shown in the right panel of Fig. 1. Therefore having a precise measurement of the amplitude of the present day matter power spectrum in comparison to the CMB spectrum provides a means to constrain the sum of all neutrino masses. The galaxy cluster mass function is exponentially sensitive to the amplitude of the matter power spectrum on scales of the order of 10 Mpc. Therefore galaxy clusters provide an ideal tool to measure this effect of neutrinos if combined with precise measurements of the CMB.

3. Probing cosmological parameters and neutrino masses with the REFLEX galaxy cluster sample

For the construction of the cluster mass function, a statistically complete survey of galaxy clusters with known masses is required. One of the best ways to obtain such a sample remains an X-ray survey, since X-ray emission of the hot ICM (few

$\times 10^7$ K plasma) is an unambiguous indication of a massive gravitational potential and the X-ray luminosity is closely related to the total mass of a clusters (e.g. Pratt et al. 2009, Böhringer et al. 2012). With the main goal to conduct cosmological studies of this kind, we have been performing large X-ray galaxy cluster surveys based on the ROSAT All-Sky Survey (Trümper 1993, Voges et al. 1999) with an extensive spectroscopic follow-up program (Böhringer et al. 2000, 2001, 2004, 2013, Chon & Böhringer 2012). The REFLEX II galaxy cluster survey covers the southern sky below equatorial latitude $+2.5^\circ$ and at galactic latitude $|b_{II}| \geq 20^\circ$, excluding the Magellanic Cloud regions and comprises a survey area of ~ 4.24 ster. It yielded a catalogue of 911 clusters. The nominal flux-limit is 1.8×10^{-12} erg s $^{-1}$ cm $^{-2}$ in the 0.1 - 2.4 keV energy band, which is reached in 78% of the sky. The regions where the flux limit is slightly higher are accounted for in the selection function. The source detection and characterisation, the galaxy cluster sample definition and compilation, and the construction of the survey selection function as well as tests of the completeness of the survey are described in Böhringer et al. (2013).

The X-ray luminosity of clusters is determined within a radius r_{500}^a . The cluster masses are estimated from the X-ray luminosities with the scaling relation (Böhringer et al. 2013), $M_{500} = 2.48 L_{500}^{0.62} E(z)^{-1} h_{70}^{-0.242}$, where M_{500} is the mass inside a radius of r_{500} , $E(z) = (\Omega_m(1+z)^3 + \Omega_\Lambda)^{1/2}$, and h_{70} is the Hubble constant in units of 70 km s $^{-1}$ Mpc $^{-1}$. This relation was derived in a detailed study of a representative subsample of REFLEX galaxy clusters, REXCESS (Böhringer et al. 2007, Pratt et al. 2009). From this cluster sample with the well known survey selection function we can construct the X-ray luminosity function with high precision.

To obtain cosmological model parameter constraints, the theoretical predictions for the cluster X-ray luminosity function are compared with the observations from the REFLEX II project, as described in Böhringer et al. 2014. The prediction of the X-ray luminosity function involves the following steps: First the power spectrum of the matter density fluctuations for the present epoch is calculated with CAMB (Lewis et al. 2000)^b. Based on this power spectrum we calculated the cluster mass function with the formulas given by Tinker et al. (2008). From the mass function the X-ray luminosity function is derived using an empirical X-ray luminosity–mass relation given above, based on the results from the REXCESS survey (Pratt et al. 2009), in good agreement with Vikhlinin et al. (2009) and Reiprich & Böhringer (2002).

In determining best fit model parameters through a likelihood analysis, we marginalised over an uncertainty of the scaling relation slope of 7% and normalisation of 14%. A scatter of the relation of 30% and a typical measurement uncertainty for the X-ray luminosity of 20% were taken into account.

^a r_{500} is the radius where the average mass density inside reaches 500 times the critical density of the Universe at the epoch of observation.

^b CAMB is publicly available from <http://www.camb.info>

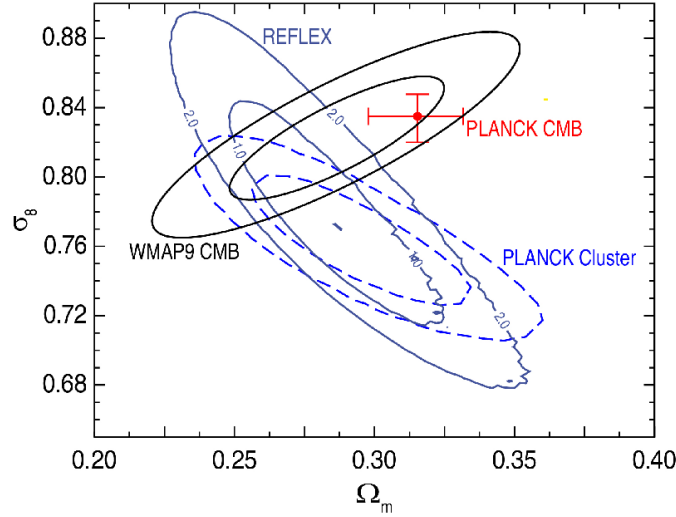


Fig. 2. Constraints on Ω_m and σ_8 from the REFLEX II X-ray luminosity function. The contours give the 1 and 2σ confidence intervals. We compare this result to the constraints from the galaxy cluster sample from Planck and the constraints from the Planck and WMAP CMB analysis.

Galaxy clusters are best at providing constraints on the cosmological parameters, Ω_m , and σ_8 . The constraints for these parameters are shown in Fig. 2, where we compare our results to the constraints from an analysis of the galaxy cluster population detected in the Planck Survey (Planck Collaboration 2015b). There is excellent agreement between the two results. The Planck cluster sample is based on very different selection criteria and covers a larger redshift range, providing confirmation for the selection strategy in both surveys. We also compare these results to the constraints derived from the CMB anisotropies with WMAP (Hinshaw et al. 2013) and Planck (Planck Collaboration 2015a). With the improved precision of the Planck results, a discrepancy between the cluster and the CMB parameter constraints now becomes apparent. Note that the comparison is made with observations of the Universe at very different epochs. Thus the comparison is model dependent and has only been performed here for a sum of the neutrino masses of 0.06 eV (Planck Collaboration 2015a). It has to be seen if the discrepancy can be reconciled with a different cosmological model (e.g. including more massive neutrinos).

4. Constraints on the mass of the three neutrino families

In the left panel of Fig. 3 we show the constraints on Ω_m and σ_8 obtained from the REFLEX sample when we allow the neutrinos to have masses in the range $M_\nu = 0 - 0.6$ eV. Since σ_8 normalises the matter power spectrum at a scale of $8h^{-1}$ Mpc, the effect of the neutrinos is almost normalised out. To reveal the effect more clearly and to better compare with the Planck results, we chose a different normalisation of the power spectrum, taken at large scales at the time of recombination with the

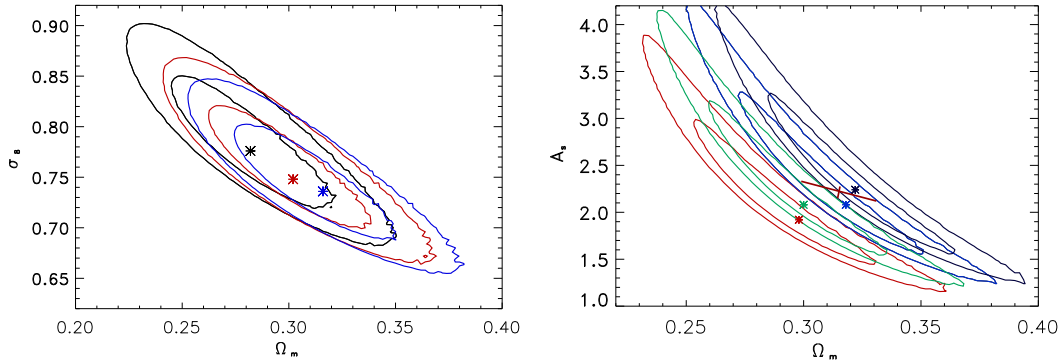


Fig. 3. **Left:** Constraints on Ω_m and σ_8 from the REFLEX II X-ray luminosity function for $M_\nu = 0, 0.17, 0.4$, and 0.6 eV, for the contours from bottom to top, respectively. The contours give the 1 and 2σ confidence intervals. **Right:** Constraints on A_s and σ_8 from the REFLEX II X-ray luminosity function for $M_\nu = 0, 0.17, 0.4$, and 0.6 eV, for the contours from bottom to top, respectively. The contours give the 1 and 2σ confidence intervals. We also show the constraints derived from the Planck CMB observations (data point with 1σ errors bars).

parameter A_s , also used for Planck. The result is shown in the right panel of Fig. 3. Due to the small change of the CMB power spectrum (as shown in Fig. 1), the CMB constraints hardly change with varying neutrino mass and we show only one data point for the Planck CMB. For the REFLEX data we show the constraints for four different total neutrino masses, $M_\nu = 0, 0.17, 0.4, 0.6$ eV. We note that the constraints are in agreement for neutrino masses in the range $M_\nu = 0.45 \pm 0.28$ eV (1σ confidence, Böhringer & Chon 2015). It is quite striking how the lightest particles in the Universe with masses of few 10^{-37} kg can influence the most massive systems, galaxy clusters, with masses of the order of 10^{48} kg.

5. Systematics

The precision of the current results of cosmological studies with galaxy clusters is limited by systematics, mostly by the accuracy of the cluster mass estimates. The present study rests on the calibration of the X-ray luminosity–mass relation with deep X-ray studies, for which hydrostatic equilibrium and spherical symmetry of the clusters were assumed. We know from detailed numerical hydrodynamical studies, that this mass measurement is biased low by about 10 - 25% because of the neglect of dynamical pressure of the ICM. In our analysis we have assumed that the hydrostatic masses are biased low by 10% and adopted an additional uncertainty of 14%.

Another source of information on the possible mass bias comes from the comparison of X-ray determined hydrostatic masses with cluster masses derived from weak gravitational lensing analyses. While the latter measurement has a substantial individual scatter, it is believed to have a very small bias (e.g. Becker & Kravtsov

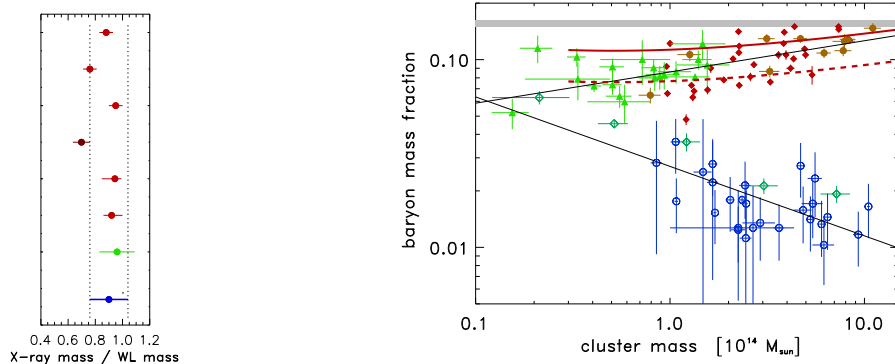


Fig. 4. **Left:** Ratios of cluster masses determined by X-ray observations to those from gravitational lensing studies and their uncertainties for several cluster samples. The lowest data point gives the mass bias and its uncertainty assumed in our analysis of the REFLEX sample. **Right:** Gas (filled symbols) and stellar mass fractions (open symbols) from Vikhlinin et al. 2006 (circles), Pratt et al. 2009 (diamonds), Sun et al. 2009 (triangles), Lin et al. 2003 (open circles), and Giodini et al. 2009 (binned data, open diamonds). The solid lines are (from bottom to top), fitted power laws to the stellar and gas mass fractions and the total baryon fraction as the sum of the two. The grey shaded area shows the cosmic baryon fraction (Planck Collaboration 2015a) and the dashed line indicates the value for the cluster baryon fraction if a mass bias of 32% would have been adopted.

2003). Recent results of the comparison of X-ray or Sunyaev-Zeldovich effect based mass measurements with weak lensing studies have produced results ranging from almost no bias to bias values as large as 32% (e.g. Mahdavi et al. 2013, Hoeckstra et al. 2015, Smith et al. 2016), where the bias value here indicates the mass underestimate by the X-ray analysis. If the bias would be larger than 30%, the significance of the neutrino mass signal is lost (e.g. Planck Collaboration 2015c, Mantz et al. 2015). In the left panel of Fig. 4 we compare the range of the mass bias ratios from the lensing results to our marginalisation, and apart from one outlier data point, our marginalisation covers the observational results for the mass calibration very well.

There is a good argument to rule out extreme values of hydrostatic mass bias. The gas mass of the intracluster medium can be determined more easily than the total mass of a cluster. Since galaxy clusters are assembling cosmic matter almost indiscriminantly into their gravitational potential, we expect an almost exact cosmic ratio of the mass in baryons to that of the dark matter. In Fig. 4 we compare the fraction of the total mass contained in gas and in stars to the total matter. We also compare the summed baryon mass fraction with the cosmic ratio determined with Planck. We see that the cluster baryon fraction falls short of the cosmic ratio, but less so for the most massive clusters. The reason for the discrepancy is extra heat which is deposited in the gas during galaxy and active galactic nuclei evolution, which inflates the gas halo and pushes some of the baryonic matter beyond the fiducial radius of a cluster. This has little effect on the most massive clusters with deep

gravitational potentials. For the data shown in Fig. 4 the total cluster masses have been determined assuming hydrostatic equilibrium. A small mass bias correction could be tolerated in this study. But a mass bias as large as 30% would imply that almost half the baryons, mostly in the gas, have to be pushed out of the cluster potentials even in the most massive clusters. This is extremely unlikely given the large energy input needed and based on the experience with hydrodynamic simulations of cluster formation.

6. Comparison to other large-scale structure measurements

The effect of massive neutrinos is best revealed through the comparison of the density fluctuation amplitude of the present epoch LSS and the prediction of the Λ CDM model based on the Planck results. Therefore it is interesting to check if other nearby LSS assessments, like LSS gravitational lensing, the galaxy clustering power spectrum amplitude, redshift space distortion effects in the galaxy correlation function, CMB lensing, and the study of the structure of the Ly α forest show a similar trend requiring massive neutrinos. This has been found in some of these studies, which in particular involve the study of lensing and redshift space distortions as well as clusters: Beutler et al. (2014) found $M_\nu = 0.36 \pm 0.14$ eV (1σ) from the SDSS power spectrum and redshift space distortion effects in comparison with the CMB, Costanzi et al. (2014) obtain a result of $M_\nu = 0.29^{+0.18}_{-0.21}$ eV comparing lensing and cluster observations to CMB results, also Ruiz & Huterer (2015), Battye & Moss (2013), Hamann & Hasenkamp (2013), and Wyman et al. (2014) find evidence for a non-zero neutrino mass based on lensing and/or cluster observations. All these results are in good agreement with our results from the REFLEX cluster survey. Analyses of just the galaxy power spectrum or the power spectrum of the Ly α forest have recently produced only upper limits, which are quite tight and only marginally consistent with our results. Among those are the study of Riemer-Sørensen et al. (2014) and Cuesta et al. (2015) who combined the SDSS and WiggleZ galaxy power spectrum with BAO signatures and the Planck results finding $M_\nu \leq 0.18$ eV and $M_\nu \leq 0.12$ eV, respectively. Also Ly α studies yielded lower upper limits, of e.g. $M_\nu \leq 0.17$ (Seljak et al. 2006) and $M_\nu \leq 0.12$ (Palanque-Dellabriouille et al. 2015). Massive neutrinos also have a subtle effect the CMB measurable with Planck yielding $M_\nu \leq 0.49$ eV. Combined with BAO observations (which are not sensitive to LSS amplitudes, but help to break degeneracies in the set of cosmological parameters) the limit is $M_\nu \leq 0.21$ eV (Planck Collaboration 2015a). Lensing in the CMB provides another measure of the low redshift LSS. The analysis of CMB lensing in the Planck Survey (Planck Collaboration 2015b) shows indeed a trend that the lensing signal and thus the local LSS amplitude is smaller than expected from the CMB results in a Λ CDM model. Thus even so there are several indications that neutrinos have more than the minimum mass of $M_\nu = 0.06$, the overall results are not in perfect agreement.

7. Summary and Conclusion

Cosmological studies with *Planck* together with LSS observations have clearly shown that a background of cosmic neutrinos exists, providing a constraint for the effective number of neutrino species of $N_{eff} = 3.15 \pm 0.23$ (Planck Collaboration 2015a). With the particle physics lower limit for the sum of the neutrino masses of $M_\nu = 0.058$ eV, neutrinos contribute at least about 0.4% to the total matter content in the Universe and have a significant effect on the evolution of the cosmic large-scale structure. This effect is best revealed by a comparison of the *Planck* CMB study with present epoch LSS measurements.

Several such studies have provided evidence for a non-zero neutrino mass with galaxy clusters showing one of the strongest signals. We discussed here the results from the REFLEX cluster survey with the largest well-defined X-ray cluster sample for this type of study, yielding tight constraints on the cosmological parameters σ_8 and Ω_m . A comparison with the results from *Planck* suggests a sum of the neutrino masses in the range $M_\nu = 0.17 - 0.73$ eV (1σ). Other LSS measurements which show a similar trend include gravitational lensing and redshift space distortion observations, while the study of the galaxy power spectrum and the structure of the Ly α forest yield smaller upper limits which are only marginally consistent with the positive neutrino mass detections.

We have in this paper not considered sterile neutrinos. A main motivation for the inclusion of sterile neutrinos in cosmological models was the discrepancy in the Hubble constant determined locally (inside a radius smaller than 200 Mpc) and with *Planck*. We have recently shown, based on the distribution of galaxy clusters, that we live in a locally underdense region in the Universe, at least for the southern sky region (Boehringer et al. 2015), which can at least resolve a part of the tension between the local Hubble constant measurements and *Planck*.

All these studies are systematics limited. For clusters the most serious limiting systematic is the cluster mass calibration. Large efforts are currently underway to beat down these uncertainties, to fully exploit the potential of a cosmological neutrino mass measurement. Several future surveys include constraining of the neutrino mass as an important science goal, for example, the sky surveys with DESI, LSST and EUCLID and possibly a new advanced CMB mission. The aim for these projects is an uncertainty of $\Delta M_\nu \sim 0.025(0.016)$ eV and $N_{eff} \sim 0.08(0.02)$, where the numbers in brackets refer to results including an advanced CMB mission (e.g. Abazajian et al. 2015). With this outlook we can hope that the currently more qualitative results can turn into a fundamental precision measurement for particle physics.

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